Available online at www.sciencedirect.com

SciVerse ScienceDirect

Physics Procedia 36 (2012) 94 – 99

Physics Procedia

Superconductivity Centennial Conference

Universal character of tunnel conductivity of metal-insulator-metal heterostructures with nanosized oxide barriers.

V.Shaternik[a] , M. Belogolovskii[b], T.Prikhna[c], A.Shapovalov[c], O.Prokopenko[d], D. Jabko[d], O.Kudrja[d], O.Suvorov[a], V.Noskov[a] a*

[a] *G.V.Kurdyumov Institute for Metal Physics of National Academy of Sciences of Ukraine, Kyiv -142, Ukraine*
[b] *Donetsk Institute for Physics and Engineering, National Academy of Sciences of Ukraine, Donetsk, Ukraine*
[c] *Institute for Superhard Materials of National Academy of Sciences of Ukraine, Kyiv, Ukraine;*
[d] *T. Shevchenko National University of Kyiv, Faculty of radiophysics, Kyiv, Ukraine*

Abstract

We discuss an universal effect in tunnel characteristics of layered metal - insulator – metal structures, where the dielectric barrier is formed by a nanoscale disordered oxide film: a universal distribution of the insulator layer transparencies, which does not depend on specific microscopic characteristics of it. Experimental results for superconducting three- and four-layered structures with inhomogeneous tunnel barriers, confirming the existence of a universal distribution of transparencies, are given jointly with a simple theoretical interpretation, based on the equipartition hypothesis of a product of the barrier height on the way which an electron passes within it.

Keywords: Josephson junction; multiple Andreev reflection; transparency distribution; quasiparticle, I-V curve, barrier

Four-layered MoRe–Al–Al_xO_y – MoRe Josephson junctions have been fabricated and investigated experimentally. MoRe superconducting thin films (T_c~9 K) with thickness 100-200 nm are deposited on Al_2O_3 substrates at room temperature by dc magnetron sputtering of target in vacuum. Al thin films are deposited on MoRe film surfaces by e-beam evaporation of aluminum in various technological conditions (mainly, at various values of the rate of deposition) to vary the transparency

* Corresponding author.
E-mail address: shaternik@mail.ru

1875-3892 doi:10.1016/j.phpro.2012.06.052

distribution functions in the fabricated junctions. Al_xO_y tunnel barriers are formed by oxidation of the Al layers in dry oxygen at various values of the oxygen pressure in vacuum chamber. Then the top MoRe layer are deposited on the Al_xO_y layer in the same conditions as described earlier. The quasiparticle I-V curves of the fabricated Josephson junctions are measured experimentally at T=4.2 to estimate the transparency distribution functions in the fabricated junctions by computer simulation of its in frame of the well-known theory model of multiple Andreev reflections [1], these I-V curves are given in fig.1 and fig.2 jointly with the calculated ones.

In the frame of well known Landauer – Büttiker approach [2,3] the transport properties of quantum-coherent mesoscopic conductor, including it conductivity and noise characteristics, are determined in whole by a set of coefficients of transmission t_l, which are described as eigenvalues of the it matrix of scattering. This matrix of scattering connects the states of the incoming electrons (into the conductor) with the corresponding states of the outgoing electrons. So, index *i* corresponds for various channels of conductivity. For example, in a three-dimensions planar tunnel structure metal-isolator-metal (MIM) with nanosized oxide interlayer I indexes *i* correspond for various angles of incoming, which electron momentums have in between their vectors and the normal of the junction interfaces. There is proposed also that the conductor I are connecting two reservoirs having the chemical potentials μ_1 and μ_2 Inside these reservoirs electrons have a large number of an inelastic scatterings and as a result "have lost" the information about their initial quantum-mechanical phases.

In the case of the ballistic quantum transport a specimen (I here) conductivity is described as a product of the conductivity quantum $G_0=2e^2/h$ and a number of the conducting channels N, which is equal $N{\sim}k^2_FS$ in the three dimensional case, here k_F and S are Fermi wave vector and square of the cross-section of the conductor. In the specimens which we qualify as "dirty" the investigated layer consists of the large number of the random centers of scattering, in every of them an electron are scattered in elastic manner. These scattering events doesn't change the phase coherence, and the length, in which the electron saves their phase memory can be much more then the free path length l and much more even then the length, which it would pass to diffuse through the layer. In the "dirty" metal $G<<NG_0$, although in this case the metallic character of conductivity has been saved and it means that $G>>G_0$. In the diffusive approximation $L>>l$ it conductivity is described good enough by the semiclassical theory [4].

In the three-dimensional metal mesoscopic specimens $L>>\lambda_F$, here $\lambda_F=2\pi/k_F$ is Fermi wave length. Opposite an interface can have very small thickness $L<<\lambda_F$. Let us consider the interface is "dirty" , so for it $G<<NG_0$ and besides conductivity can has non-metal character. The quantum transport through such kind interface has been theoretically investigated in 1997 by Schep and Bauer in [5]. The potential of the randomly located centers of scattering in a two-dimensional interface is suggested as a short-acting potential, and it value is changed randomly from the one center to another. In approximation of a strong scattering ($G/G_0<<N$) authors have developed the formulae of the averaging conductivity and the transparency distribution function $\rho(D)$ for the disordered interface [5] :

$$\rho(D) = \frac{\hbar G_N}{e^2}\frac{1}{D^{3/2}(1-D)^{1/2}} \qquad (1)$$

here G_N is the interface conductivity measured experimentally. From the equation (1), in particular, it follows that in the dirty metal specimens the shot noise power has the universal value, which equals $2eI/3$. This the universal value is being observed in experiment [6,7] , and this is an indirect evidence of the justification of the formula (1) for the quantum transport through the disordered interface.

To investigate a perspective of use of the Schep-Bauer relation for an interpretation of the experimental results we need obtain a measurable characteristics which strongly depend on the transparency of the oxide layer. One of such kind characteristics is I-V characteristics of the metal-isolator-metal junction in which one or both metal layer are in superconducting state. In the first time a calculation of the quasiparticle I-V curve of S-I-S junction (on the base of the averaging with taking in

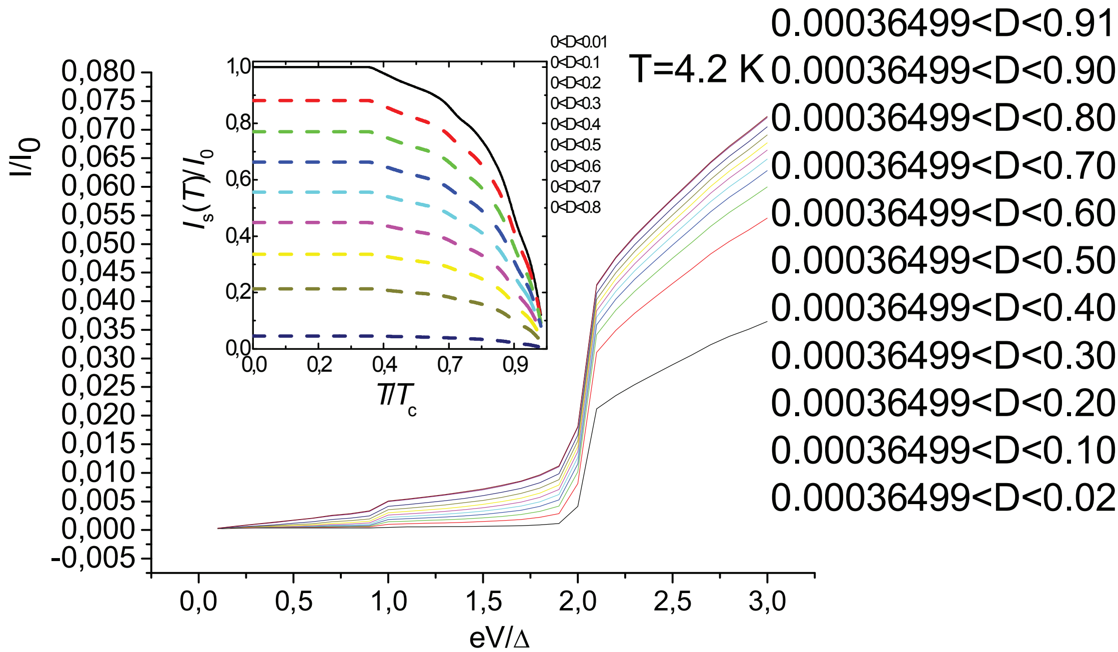

Fig.1. Calculated and experimental quasiparticle I-V curves of the Josephson junctions, fabricated at various technological parameters

account the Schep-Bauer transparency distribution function) has been done in article [8], in this article the Nb-Al_xO_y-Nb Josephson junction with the universal transparency distribution function has been fabricated and investigated. The calculations in [8] are based on the well known theory model of multiple Andreev reflections in Josephson junction [1].

Let us discuss the physical nature of the formula (1), obtained for the approximation $L<<\lambda_F$ [5]. Basing on the experimental results we propose that the applicability area of this formula is wider then the described by the condition $L<<\lambda_F$. To analyze this let us do a substitution in the Schep-Bauer calculation procedure (from paper [5]) as following $D=(1+Z^2)^{-1}$, and we obtain that the Schep-Bauer distribution (1) is transformed into a new simple formula of the δ-shape barrier height Z distribution, which doesn't depend on Z value

$$\rho(Z) = 2\,\hbar G_N / e^2 \qquad (2)$$

and the parameter Z is being changed here from the zero up to infinity. The used relation $D=(1+Z^2)^{-1}$ with

$$Z = k_F \int_0^d V_B(x)\, dx / E_F \qquad (3)$$

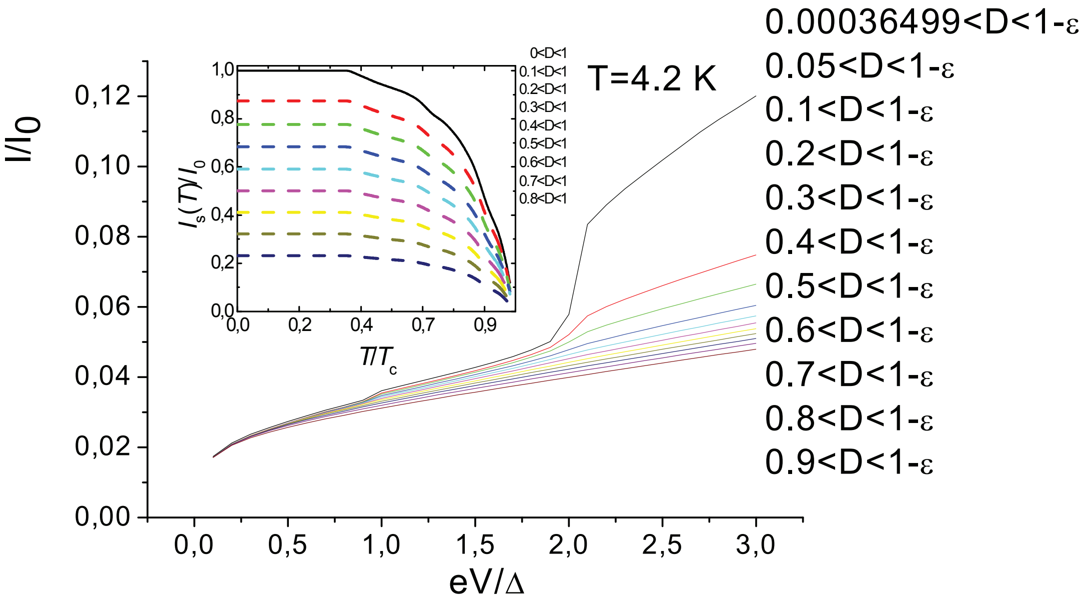

Fig.2. Calculated and experimental quasiparticle I-V curves of the Josephson junctions, fabricated at various technological parameters

(here d is a width of a potential barrier, k_F and E_F are the Fermi wave vector and Fermi energy in a metal) appears in theory in the case, when the oxide layer potential $V_B(x)$ is approximated by a one-dimensional δ-function $V_B(x) = H\,\delta(x)$, when

$$H = \int_0^d V_B(x)\, dx \tag{4}$$

[9]. It means that formula (2) describes the equiprobable distribution of values of a product of the barrier height and a way which a tunneling electron has passed into the barrier in classically forbidden region of energy. In a strongly disordered dielectric this way could be much more then the real thickness of the dielectric layer due to the existence of the elastic scattering of electrons in it crystal lattice defects. Let us stress that this interpretation of the universality of the Schep-Bauer distribution (1,2) is based on the assumption that the processes of the elastic scattering (without the lost of energy) are dominated in the dielectric layer, and this assumption is correct only for a disordered dielectric with a thickness close to one nanometer. Correspondingly, if the dielectric thickness d is increased the processes of inelastic scatterings become to play more and more important role in it.

Let us discuss once more the idea that the universality of Schep-Bauer distribution function is determined by equiprobable distribution of the *Hd* products in nanosized barriers. In paper [10] a topographical map of a surface of MgO films has been written by the atomic-force microscope scanning. And here there was observed that the MgO film surface is very smooth. Simultaneously the dependence of tunnel current through a special point contact in between a metal tip and a metal underlayer (deposited under the investigated very thin MgO layer) has been investigated as a function of the same coordinates of the scanning. The measured tunnel current space distribution is very nonuniform despite the smoothness of the MgO layer is unchanged from one coordinate to another. The disappearing of any correlations between these both characteristics means that the reason of the tunnel current fluctuations appearance is a random distribution of oxygen vacancies in the MgO layer [10]. A propos in [11] there are published the experimental data that an annealing of Al-AlO_x-Al junctions in an oxygen atmosphere decreases sufficiently the low frequency *1/f* noise caused [12] by slow processes of trapping of electrons in the defects of the oxide layer and jumping of the electrons from one defect to another.

It's necessary to note the Schep-Bauer formula (1) has some insufficiencies from physical point of view. In particular it is not normed and includes the limits $D_{max}=1$ and $D_{min}=0$ which are not realizable in experiment. And in main it universality could be broken as a result of appearance of various processes of ordering in a disordered thin oxide layer. So, we think the real experimental I-V curve is a result of some averaging of the large number of I-V characteristics with various values of the parameters D, but in generally we have proposed that limit values D_{max} and D_{min} should not be 1 and 0, but it values should be obtained in every concrete case by using experimental curves and a computer simulation of it. After this these obtained D_{max} and D_{min} becomes the parameters which characterized this junction from the point of view of the concrete transparency distribution in it. In our paper there are demonstrated it's possible to change and to control the parameters of the transparency distribution function by changing the parameters of technological conditions of fabrication of oxide layers. In the same time it's known if we change, for example, a rate of deposition of nanosized layers we can fabricate these layers with various crystal structures – single crystal, poly-crystal with defects, amorphous, amorphous with the rests of ordering etc. Schep-Bauer relation is describing an amorphous layer in firstly, so the main task of our investigation is a comparative analysis of the ρ(D) functions for the barriers created in various crystal states. For this the quasiparticle I-V curves (and dI/dV(V) curves) of the fabricated MoRe-Al_xO_y-MoRe tunnel junctions have been measured, the obtained experimental curves were compared with the calculated ones which were obtained by averaging of the theory I-V curves (for various D) by using formula (1) with two adjustable parameters D_{max} and D_{min} (see fig.1, fig.2)

$$I_{aver} = \int_{D_{min}}^{D_{max}} dD\rho(D)\, I(D) \tag{5}$$

Good coincidence of the experimental and calculated curves and observation in it's the subgap structures demonstrates and confirms that here really the transparency dispersion is described by distribution (1). But in contrast for [5] now D is changed in some narrowed region, edges of which are determined by the degree of imperfection of the oxide layer (for smooth Al_xO_x films with ν_{dep} = 10 nm/s the transparency *D* is almost the same in various barrier areas, but for rough Al_xO_x films with ν_{dep} = 1 nm/s the transparency *D* is changed strongly from the close to zero up to 0.9). So, it means the computer simulation of the quantum transport in a layered metal-isolator-metal structures requires, generally speaking, more detail taking in account of the transparency distribution in the investigated oxide tunnel layers. And for this purpose it is possible to use the universal transparency distribution *ρ(D)* in two equivalent forms (1) and (2) but with the limiting values D_{max} and D_{min} , which are determined by the properties of the individual barrier.

Conclusion

There given the experimental evidences which confirm the existence of the universal phenomenon in the tunnel characteristics of the metal-dielectric-metal heterostructures with the nanosized disordered films of oxide (dielectric tunnel barrier) - the universal and modified universal transparency distributions for the nanosized dielectric layer in the tunnel junction. This effect can be interpreted on the base of a hypothesis that the Hd product distribution (here H is barrier height, d is the electron pass in the barrier) is equiprobable in tunnel barrier with the thickness close 1 nm.

References

[1] A. Bardas and D. V. Averin, *Phys. Rev. B*, **56**, N. 14: R8518 (1997).
[2] R. Landauer, *IBM J. Res. Develop.,* **1**: 223 (1957); R. Landauer, *Philos. Mag.,* **21:** 863 (1970).
[3] M. Büttiker, Y. Imry, R. Landauer et al., *Phys. Rev. B*, **31**: 6207 (1985).
[4] B. K. Nikolić and P. B. Allen, *Phys. Rev. B*, **63**: R020201 (2001).
[5] K. M. Schep and G. E. W. Bauer, *Phys. Rev. Lett.,* **78**: 3015 (1997).
[6] A. H. Steinbach, J. M. Martinis, and M. H. Devoret, *Phys. Rev. Lett*., **76**: 3806 (1996).
[7] R. J. Schoelkopf, P. J. Burke, A. Kozhevnikov et al., *Phys. Rev. Lett*., **78**: 3370 (1997).
[8] Y. Naveh, V. Patel, D.V. Averin et al., *Phys. Rev. Lett*., **85**: 5404 (2000).
[9] G. Blonder, M. Tinkham, and T. Klapwijk, *Phys. Rev. B*, **25**: 4515 (1982).
[10] D. J. Kim, W. S. Choi, F. Schleicher et al., arxiv:1010.2473 (2010), препринт.
[11] J. K. Julin, P. J. Koppinen, and I. J. Maasilta, *Appl. Phys. Lett.,* **97**: 152501 (2010).
[12] C. T. Rogers and R. A. Buhrman, *Phys. Rev. Lett*., **53**: 1272 (1984).